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Title: **A Theory of Interoperability Failures**

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A Theory of Interoperability Failures

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Abstract

This paper develops a theory of interoperability failures. Interoperability in this paper refers to the exchange of information and the use of information, once exchanged, between two or more systems. The need for a theory of interoperability failures is introduced along with a discussion of the reinforcing relationship between theory and experiment. First, the interoperability of two systems over time is considered. The failure rate for electronic equipment as it ages over time often follows a life distribution model in the shape of the widely known "Bathtub" curve. By analogy, if one considers the interaction of two systems over time, a theory of interoperability failures can be developed by postulating a life distribution model with three distinct time periods: early, mediate, and relative obsolescence. A causal analysis that focuses on intended functionality, requirements, design implementation, and developmental testing is used to explain the existence of these three time periods. Then, the relationship between interoperability and complexity in terms of interaction and coupling is discussed. Finally, the theory is used to develop criteria for selecting specific systems to study and collect data to refute or lend credence to the theory.

1. Introduction

Achieving interoperability among Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) systems continues to be a challenge for the U.S. Department of Defense (DoD). Progress has been made in recent years through the use of directives, efforts to educate and train practitioners, an increased emphasis on capability over platforms, and the increased use of integrated architectures and mission capability packages.

One element missing from this mix is a coherent, verifiable theory of interoperability failures that captures the causes of interoperability faults in a form that practitioners can use to avoid these pitfalls in their own work.

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The purpose of this paper is to develop a theory of interoperability failures that can be confirmed by objective evidence.

The goal of developing a theory of interoperability failures is to be able to efficiently collect the data required to create and validate prediction rules that can be used to make diagnostic decisions about conducting end-to-end interoperability testing of C4ISR equipment strings. [McBeth, 2000]

Interoperability is an active area of research. The roots of the theory developed in this paper can be traced to previous work including a paper by Sutton where an analogy is drawn between interoperability and electronic equipment reliability and papers by Hamilton, Melear, and Endicott where interoperability is dealt with using an engineering life cycle model [Sutton, 1999] [Hamilton et al., 2002a] [Hamilton et al., 2002b].

In section 2, several definitions of interoperability are discussed. The relationship between the definition one adopts for interoperability and the problem to be solved is examined. A working definition of an interoperability failure is introduced. Section 3 addresses the question of why a theory of interoperability failures is needed. Section 4 extends Sutton's electronic equipment reliability analogy to gain insights into the interoperability interaction between two systems over time. This analysis suggests a notional life distribution model with three regions where specific interoperability mechanisms tend to dominate. These three regions are called the early, mediate, and relative obsolescence failure periods. Section 5 discusses the relationship of interoperability and complexity in terms of system interaction and coupling. These ideas will be used to help guide the selection of systems for study within each of these regions. Sections 6, 7, and 8 discuss the early, mediate, and relative obsolescence failure periods, respectively. In each of these three sections, causal relationships are proposed for each failure mechanism and a hypothesis is generated to explain the nature of the failure mechanism expected to dominate. Also, system selection criteria are proposed to look for evidence to refute or lend credence to the theory. Section 9 briefly introduces some ideas for creating a prediction rule based on the theory. Section 10 describes the next steps in motivating and verifying the theory. Section 11 provides a brief summary of the paper.

2. Interoperability Definitions

The standard DoD definition of interoperability is:

> "(1) The ability of the systems, units, or forces to provide services to and accept services from other systems, units, or forces, and to use the services so exchanged to enable them to operate effectively together, and (2) the condition achieved among communications-electronics systems or items of communications-electronics equipment when information or services can be exchanged directly and satisfactorily between them or their users. The degree of interoperability should be defined when referring to specific cases." [CJCS, 2000]

This definition is all-encompassing and stated at a high level of abstraction to cover a wide variety of situations. The definition was modified from the previous release of the instruction to

acknowledge that the "degree of interoperability" is case dependent and "for the purposes of this instruction ... will be determined by the accomplishment of the proposed Information Exchange Requirement (IER) fields." [CJCS, 2000] The notion of an IER implies an "end-to-end" thread or string that allows users to exchange information through a C4ISR architecture. Sutton recognized the need to focus on "end-to-end" interoperability and provided the following definitions:

<u>end-to-end interoperability</u> - "The probability of successful interoperation of all subscribers in a network under specified conditions for a given mission time." [Sutton, 1999]

<u>interoperability failure</u> - "The inability of the network to meet specified interoperability levels, conditions, and requirements, such as minimum acceptable data transfer rate, quality of service, and maximum allowable latency." [Sutton, 1999]

Although these definitions may work at a network level, they fall short for defining interoperability at the end-to-end thread or string level. These definitions allow problems including faulty network design, improper traffic management, and intrinsic hardware failures to serve as potential causes for interoperability failures. While one can argue that these are serious problems, they are unlikely to be detected in traditional lab-based end-to-end testing since these problems are not directly related to the interactions between two or more systems.

For example, although intrinsic hardware failures in a system can render a *specific instance* of an equipment string and its corresponding functional thread <u>inoperative</u>, it is not a sign that the equipment string, per se, is not <u>interoperable</u>. This may seem like a fine distinction, but it is a critical one if the definition of interoperability is to lead to prediction rules useful for selecting equipment strings for end-to-end testing. Including causal indicators for intrinsic hardware failures in a prediction rule could result in a diagnostic protocol with an unacceptably high (and costly) false alarm rate. Therefore, traditional Mean-Time-Between-Failure (MTBF)-type failures, which are unlikely to be detected during end-to-end testing, should be excluded. These failures are more of a reliability issue that can be better addressed through well known design measures and reliability growth testing. [Fuqua, 1987]

With the dual principles of system interaction and end-to-end testing in mind, definitions for an equipment string and a functional thread are presented. These definitions will set the stage for working definitions for interoperability, interoperability failure, and interoperability fault.

<u>equipment string</u> - a serial sequence of N systems connected with N-1 links that provides a communication path between users to exchange information.

<u>functional thread</u> - a construct consisting of the *equipment string* input, *equipment string* output, a description of the transformations to be performed, and the conditions under which this should occur. [INCOSE, 2000]

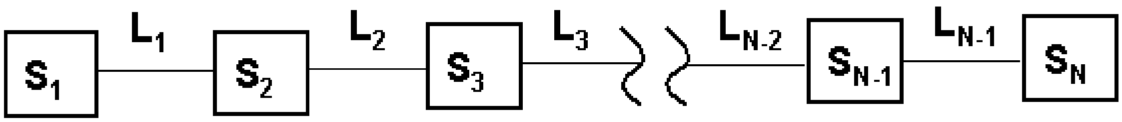

Figure 1. Graphical representation of an equipment string.

Mathematically, an equipment string can be viewed as a type of connected graph having no cycles called a *tree*. Equipment strings are trees with no vertex having a degree greater than two. [Chartrand, 1977] This connection to graph theory may open equipment string analysis to a host of theorems and results from mathematics. A detailed application of graph theory to equipment strings is left for future work. A paper by Coudert and Muňoz gives a flavor of how graph theory has been applied to similar communications engineering problems. [Coudert & Muňoz, 2001]

The functional thread definition above is adapted from the International Council on Systems Engineering's (INCOSE) definition of a stimulus-condition-response thread. Conceptually, an equipment string is a means of defining a communications path between users and a functional thread is a way of defining the behavior of the string with respect to how information is exchanged and used.

Interoperability failures of concern here deal with the <u>interaction</u> and <u>coupling</u> of two or more systems. The following are provided as working definitions for this paper:

<u>Interoperability</u> - "the ability of two or more systems to exchange information and to mutually use the information that has been exchanged." [IEEE, 1988]

<u>Interoperability fault</u> - a defect or condition related to system interaction that causes a reproducible malfunction in the ability of two or more systems to exchange information and to mutually use the information that has been exchanged. *Note:* a malfunction is considered reproducible if it occurs consistently under the same circumstances. [Adapted from FS-1037C, 1996]

<u>Interoperability failure</u> - the inability, due to an interoperability fault, of two or more systems to exchange information and to mutually use the information that has been exchanged.

These definitions are not limited to C4ISR equipment strings and functional threads. However, they do cover the central issues of interoperability at the end-to-end thread or string level discussed above. One should think of these interoperability definitions as being associated with the interaction of systems composed of specific hardware and software releases.

The wording of these definitions needs to be precise since they drive the problem statement that is used to develop the theory of interoperability failures in this paper.

3. Why a theory of interoperability failures?

> *The primary purpose of any theory is to clarify concepts and ideas that have become, as it were, confused and entangled. Not until terms and concepts have been defined can one hope to make any progress in examining the question clearly and simply and expect the reader to share one's views.*
>
> -- Carl Von Clausewitz
> *On War*

A theory of interoperability failures is needed to guide the collection of data required to identify causal indicators and build statistical prediction rules for selecting end-to-end equipment strings for interoperability testing. Previous efforts to achieve a sound understanding and model for end-to-end interoperability performance have been hampered by a lack of data collection and analysis to quantify the relationships between interoperability performance and its contributing factors. This has primarily been due to the large number of potential contributing factors that exist to be studied.

A sound working theory of interoperability failures can help overcome this situation by "informing" and guiding the experimental designs to focus on the contributing factors that are most closely related to the mechanisms and modes suspected to be responsible for interoperability faults and failures.

The reinforcing relationship between theory and experiment is depicted in figure 2 where a curious observation leads to the construction of a plausible concept. A plausible concept is further manipulated through the logical processes of abduction to provide explanations, induction to provide generalizations, and deduction to provide consistency. [Flach & Kakas, 2000]

These logical processes lead to hypotheses and models which inform the design of experiments where measurements are made to collect and analyze data leading to interpreted results. These interpreted results serve to provide evidence for or against the theory being tested. The theory and experiment process can be seen as one form of the scientific method.

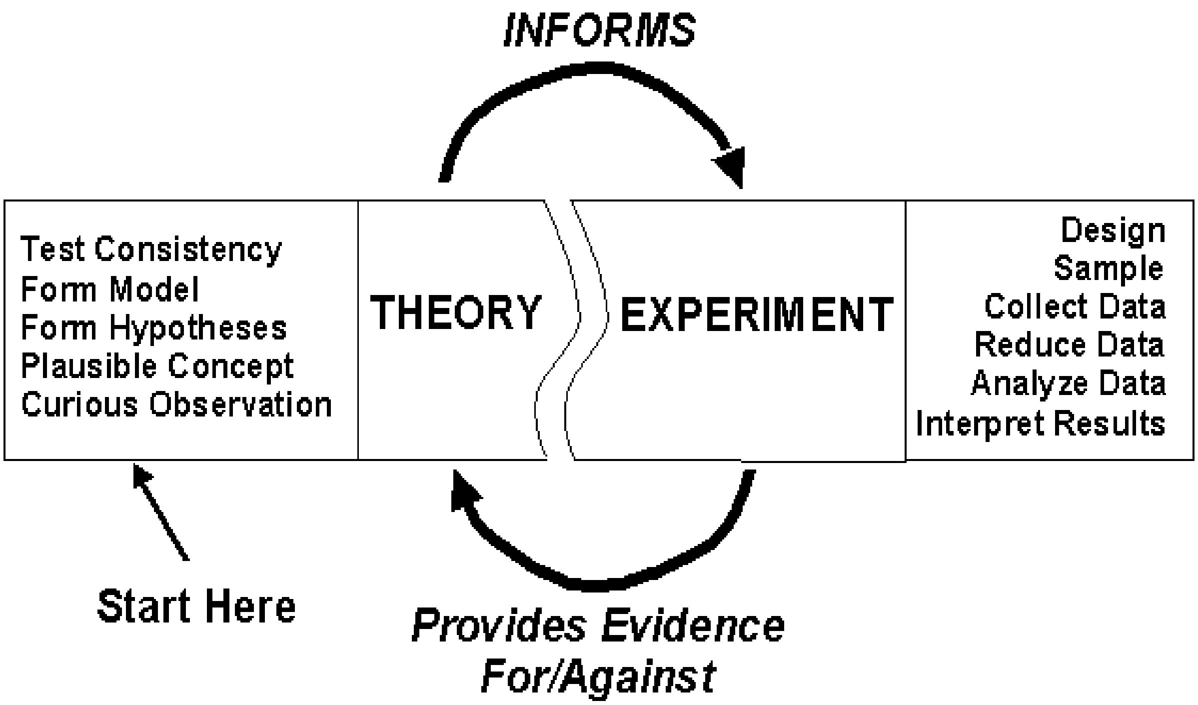

Figure 2. An idealized depiction of the reinforcing relationship between theory and experiment.

There are several examples of where theory has guided experiment toward new knowledge. The most famous example is that of Albert Einstein's 1905 Special Theory of Relativity which used arguments of symmetry and invariance to transform the science of mechanics. [Weinberg, 2001]

A theory of interoperability failures allows one to narrow the focus of investigation to a certain set of facts. For example, suppose it is believed that the number and scale of hardware or software upgrades in one system relative to another is positively correlated to the likelihood of an interoperability failure occurring between these systems. In this case, one might begin to study this aspect of interoperability failures by looking at older, legacy systems to see what problems have occurred when other systems they interoperate with have been more rapidly upgraded.

Obtaining a sound theory of interoperability failures is useful beyond guiding the data collection required to build a prediction rule for end-to-end testing of C4ISR equipment strings. Sutton states that "it will be possible to determine how effective directives, strategies, objectives, plans, and other factors are in improving interoperability [only once we have] a theory of interoperability that can be confirmed by repeatable experiments and improved through consistent empirical data collection and analysis." [Sutton, 1999]

4. Interoperability over time: Extending Sutton's Analogy

Paul Sutton's paper, "Interoperability: A New Paradigm," provides a refreshing discussion of interoperability that in large part influenced the direction of the work in this paper. His critique of the shortcomings of the Levels of Information Systems Interoperability (LISI) descriptive model resonate with this author's experience in trying to use LISI as the basis of a diagnostic prediction tool. Specifically, Sutton identifies five "significant deficiencies" in the LISI model:

> "First, it does not address specific electrical interfaces, which are necessary for simple connectivity between system components, a necessary but insufficient condition for interoperability. Second, it does not address the issue of compatible objects and object models ... Third, it assigns nominal values to the degree of interoperability between two different systems which are based on system documentation, but does not provide any objective system performance measures that are based on actual operation of the systems. Fourth, its method of assigning interoperability scores doesn't take into account the fact that some systems may not need to connect to other systems at higher levels of interoperability to be considered successful. Finally, it does not explain how interoperability can be controlled, changed, or improved." [Sutton, 1999]

Sutton draws on the analogy of electronic equipment reliability to postulate a theory of interoperability failures (Sutton uses the term interoperability performance). [Sutton, 1999] However, his assumptions for random interoperability failures and a constant interoperation failure rate can be seen as being too optimistic. This leads to a model that is too simple to be useful as the basis of a prediction rule. Consequently, this theory of interoperability failures lacks sufficient "relation-structure to the process it models." [Johnson-Laird, 1983] Thus a large list of potential contributing factors emerges leading to a data collection and analysis effort that is expensive, time consuming, and likely never to be undertaken. What is needed is a theory of interoperability failures that simplifies the task of collecting the data required to quantify the relationships between interoperability and its contributing factors.

By challenging the assumption of a constant interoperability failure rate and carefully considering the failure mechanisms of electronic equipment, it is possible to draw a more useful analogy. Consider that the failure rate for electronic and mechanical equipment as they age over time often follows a life distribution model in the shape of the widely known "Bathtub" curve. [NIST, 2003, Section 8.1.2.4]

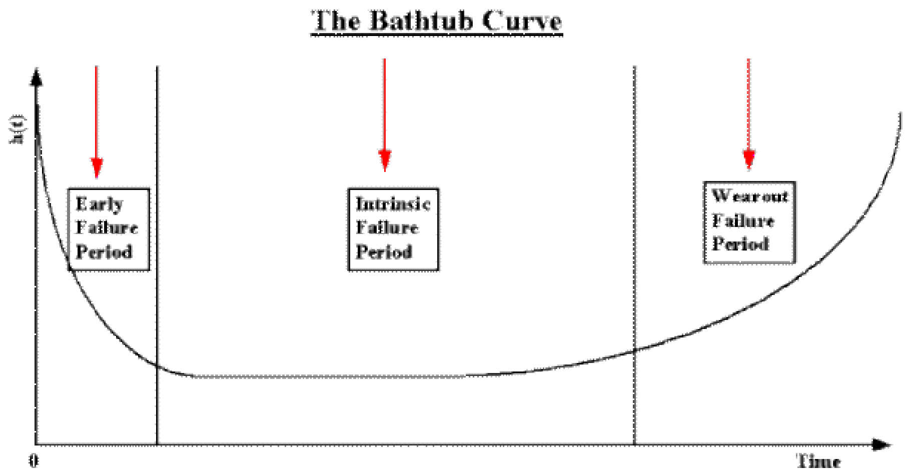

Figure 3. "Bathtub" curve life distribution model for the failure rates typically found for electronic and mechanical equipment. Source: Adapted from NIST, 2003, Section 8.1.2.4.

To fully appreciate the development of this analogy, it helps to review some details of the Bathtub curve as it applies to electronic equipment reliability. This life distribution has three distinct periods where specific failure mechanisms tend to dominate. The first period is called the early failure period or infant mortality period where the instantaneous failure rate starts out relatively high and then rapidly decreases over a time frame lasting from several weeks to a few months. [NIST, 2003, Section 8.1.2.4] The failure mechanisms that tend to dominate in this period are related to quality and can be attributed to variations in manufacturing processes and defects in materials resulting in "weaker parts" that cause failures during normal equipment operation. [Fuqua, 1987, p. 4.] The second period is called the intrinsic failure period which is characterized by a constant instantaneous failure rate where most equipment spend the majority of their useful lives. Here the failure mechanisms are related to quality, stress, or wear. They "are random in nature and are randomly distributed with respect to time." [Fuqua, 1987, p.4] The third period is called the wear out failure period. It is characterized by a rising instantaneous failure rate over time. The failure mechanism here tends to be dominated by "accumulated damage due to the applied stresses" causing parts to "become weaker, more prone to failure, and thus fail with increasing frequency." [Fuqua, 1987, p.6] These three periods are depicted graphically in figure 3.

The analogy between equipment failures and interoperability failures can be extended and improved if we confine our analysis to the interoperability interaction between two systems over time and assume the resulting model can be extended to equipment strings using a pair-wise comparison technique. Also to be considered is that the power of the analogy lies in the fact that different failure mechanisms may tend to dominate at different times in the history of the interaction between two systems—not that there are exactly three time periods that correspond to the bathtub curve. In other words, one should not expect the same failure mechanisms found in equipment failures to apply to interoperability failures and that the resulting life distribution

model for interoperability failures may not look like a bathtub curve. Time in this analogy is not the time since a piece of equipment has been operating, but the time that the two systems under study have been interoperating.

However, if one thinks about the interoperability interaction between two systems over time, a case can be made for three distinct periods of time where different sets of interoperability failure mechanisms tend to dominate. These three postulated time periods: early, mediate, and relative obsolescence are described below.

First, the early failure period is postulated to start with a relatively higher failure rate and decrease over time because the two systems have little or no experience interoperating with each other. Each system was created with an intended functionality that was captured in a set of requirements which, in turn, was translated into a design implementation. This design implementation was then submitted to some level of developmental testing to verify the intended functionality. Errors and inadequacies in this development process will not become evident until the two systems actually begin interacting and interoperating. The idea of using the development process or engineering life cycle as a reasonable approach to "deal with interoperability" is echoed in the writing of Hamilton, Melear, and Endicott. [Hamilton et al., 2002b] This suggests an experimental approach that focuses on collecting data about systems that have recently been introduced into service to understand the statistics of the early failure period.

Second, after the early failure period, a mediate failure period is postulated with a relatively low failure rate because the two systems have some experience and a history of interoperating with each other. Here the intended functionality has been exercised and is known to work. This period is called "mediate" because it occupies a middle position between the early failure and relative obsolescence failure periods. However, there may exist rare or infrequently used functional threads associated with equipment strings containing the two systems which trigger latent interoperability faults between the systems (think of the Year 2000 problem, for example). Additionally, there may be new modes of operation or changes in tactics, techniques, and procedures that "stretch" or "stress" the intended functionality and result in interoperability failures (think of new warfighting experiments). So the likelihood of interoperability failures would be related to the probability of these events occurring. This suggests an experimental approach that focuses on collecting data about problems resulting from systems being used in new operational contexts and exercises. Data also needs to be collected about systems that have interoperated for some time without a great difference in their relative upgrade histories.

Third, a relative obsolescence failure period is postulated with a relative failure rate that increases over time because of the introduction of newer software and hardware upgrades in one system relative to the other. The greater the number and scale of these upgrade changes the more likely interoperability failures are to occur. (think of the compatibility of software written for an 8088 microprocessor with a Pentium or trying to use files from an early version of WordPerfect with the latest release of Microsoft Word). This suggests an experimental approach that focuses on collecting data about systems that have been in service for many years and looking at the number of interoperability problems as a function of the separation in frequency and scale of system upgrades over time.

These failure periods are depicted in figure 4.

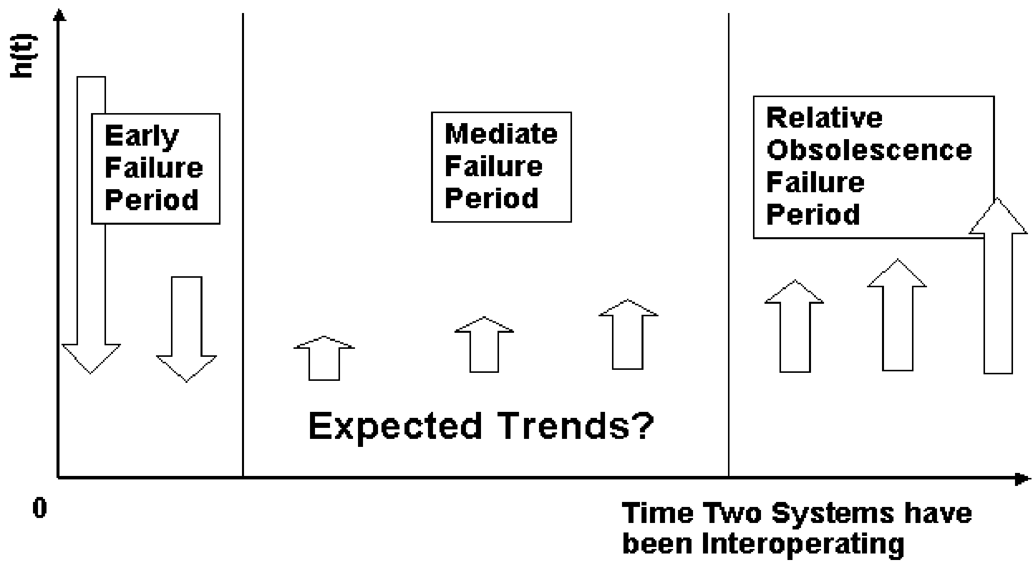

Figure 4. Postulated life distribution model for theory of interoperability failures.

Sections 6, 7, and 8 discuss each time period in more detail. For each time period, causal relationships behind the failure mechanisms are postulated and a hypothesis is generated to explain the nature of the failure mechanism expected to dominate. System selection criteria are proposed to look for evidence to refute or lend credence to the theory.

5. Interoperability and complexity: System Interaction and Coupling

There is more to the interoperability picture than a life distribution model that captures the interoperability interaction of two systems over time. The quality or nature of the interoperability between two systems can also influence the likelihood of interoperability failures. Conceptually, the interoperability between two critical real-time systems requiring multiple synchronous transactions to complete an information exchange is inherently more complicated than the interoperability between two noncritical low-speed systems requiring only a single asynchronous transaction to complete an information exchange. There are just more opportunities for things to go wrong in the more complicated information exchange case.

One way to approach interoperability and complexity is through the attributes of "interaction" and "coupling." This idea can be traced to the work of Charles Perrow in his book *Normal Accidents* and, later, to John Rushby who extended these ideas to computer systems. [Perrow, 1984, Chapter 3] [Rushby, 1994]

Rushby describes these attributes as:

> *Interaction*, which can range from "linear" to "complex," refers to the extent to which the behavior of one component in a system can affect the behavior of other components. In a simple, linear system, components affect only those others that are functionally "downstream" of them; in a more complex system, a single component may participate in many different sequences of interactions with many other components. In computer systems, the notion of "component" must include both physical and abstract entities; for example, the abstract entity "database" is a component, as are its processes and data, and also the devices that provide execution and storage. Computer systems that maintain global notions of coordination and consistency (e.g., distributed databases) are considered to have complex interactions, since activities in different locations interact with each other. [Rushby, 1994, Chapter 4, p. 42]

> *Coupling*, which can range from "loose" to "tight," refers to the extent to which there is metaphorical "slack" or "flexibility" in the system. Coupling is not an independent notion; we really have to ask "coupling to *what*?" For the preliminary analysis being undertaken here, however, we can tolerate the imprecision of the unqualified term, and supply more specificity when needed. Loosely coupled systems are usually less time constrained that tightly coupled ones, can tolerate things being done in different sequences than those expected, and may be adaptable to different assumptions than those originally considered. For example, craft industries are usually loosely coupled, whereas production lines with just-in-time inventory control are tightly coupled. Viewed as a computer system, the telephone switching network may be considered loosely coupled, since there are multiple ways to route calls, whereas most hard-real-time control systems are tightly coupled, since they depend on everything behaving as expected. [Rushby, 1994, Chapter 4, p. 42]

These ideas of interaction and coupling will be used in shaping the system selection criteria in the following three sections to insure that the quality or nature of the interoperability between two systems is considered.

6. Early Failure Period

The early failure period starts when two systems first begin interoperating with each other. What types of interoperability failure mechanisms might one expect to see dominating in this early period?

The system development process illustrated in figure 5 is useful to understand the failure mechanisms that are likely to dominate in the early failure period. The process starts with the intended functionality to satisfy a need or provide a capability. For C4ISR equipment strings this could range from providing confidentiality to prevent eavesdropping to transmitting real time imagery over the horizon. Next, this intended functionality is captured in a set of requirements.

This phase of the development process is a logical place to start looking for sources of interoperability failures. Are the intended functionality and required interoperability captured in the requirements?

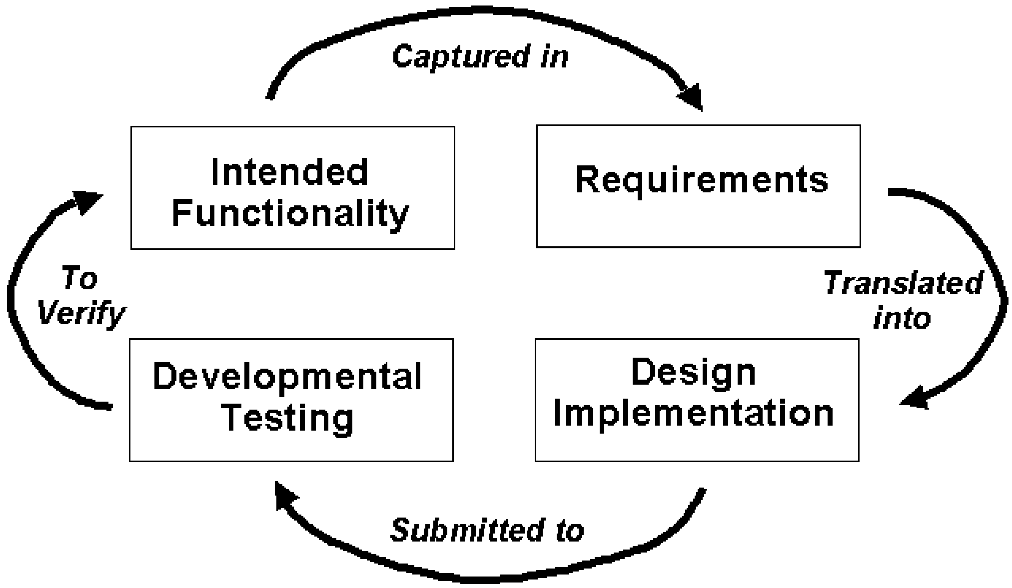

Figure 5. System development process used to discuss causal relationships for early failure period failure mechanisms.

Root causes for defects associated with the requirements phase include missing and inadequate requirements. Problems manifested from missing requirements include equipment that gets designed and built without key interfaces, protocols, and operating modes. Problems manifested from inadequate requirements include weak verification criteria that cause interoperability problems to escape detection during developmental testing and poorly defined technical performance criteria that result in timing, electrical, frequency, and mechanical mismatches.

In the next phase of the development process, requirements are translated into a design implementation. This phase provides another place to look for sources of interoperability failures. Does the design provide for the intended functionality and required interoperability captured in the requirements?

Root causes for defects associated with the design phase include waived requirements and design flaws. Problems manifested from waived requirements include those listed above for missing and inadequate requirements. Problems manifested from design flaws range from malfunctions stemming from mistakes in electrical design calculations to programming errors that cause protocol conflicts and other undesirable behavior.

In the next phase of the development process, the design implementation is submitted to developmental testing. In this phase, sources of interoperability failures are not normally introduced in the systems—instead they are not detected and screened out before the system is introduced into an operational environment.

Root causes for defects associated with the developmental testing phase include inadequate testing to verify intended functionality in the design implementation. Problems manifested from inadequate testing include those associated with weak verification criteria. This can lead to failures in the function of interfaces, protocols, and operating modes or failures in technical performance often seen as timing, electrical, frequency, or mechanical mismatches.

Ideally, one would want to adopt a standard terminology to describe these fault classes. A standard terminology makes it easier to make comparative analyses and draw general conclusions. Although the author is not aware of research community-agreed-upon standard terminology, Delores Wallace and Richard Kuhn of the U.S. National Institute of Standards and Technology have identified several fault classes based on their study of medical device failures and research into several published taxonomies. Examples of the fault types they identify include logic faults and calculation faults. Since much of interoperability performance and failures are driven by software, it seems reasonable to follow the fault analysis conventions and terminology adopted by these researchers. [Wallace & Kuhn, 1999]

This approach also makes it easier to adopt the tools and techniques they have developed and made available to the research community. This will also make it easier to compare fault distributions between application domains they have studied and the military C4ISR domain. [Wallace et al., 1997]

Based on the preceding discussion of the causal relationships postulated to be behind failure mechanisms in the early period the following hypothesis is generated:

HYPOTHESIS: Interoperability mechanisms expected to cause most failures in the early failure period stem from 1) missing or inadequate requirements, 2) design flaws, and 3) inadequate testing of the new system being introduced.

At this point, it is appropriate to consider how the preceding discussion applies to Commercial-Off-The-Shelf (COTS) and Nondevelopmental items (NDI). These items undergo the same development process shown in figure 5. In this case the development process is geared toward an application domain such as a commercial office environment which can differ greatly from a military C4ISR environment. Therefore, it is incumbent upon the acquisition agent to perform the adequate requirements, trade-off, and modification analyses to insure suitability for the intended military application. [SD-2, 1996]

The following system selection criteria and rationale are offered to guide the selection of 15 C4ISR systems for initial study to look for evidence to refute or lend credence to the hypothesis and the early failure period for a system interoperability life distribution model.

1. The system should have been introduced within the last five years. The rationale is the potential greater availability of data and information about the system's introduction.

2. The system should be new representing the first use of the system or the system should have undergone a major upgrade. The rationale is to capture the early history of system interoperability interactions.

3. The systems should include ones that are tightly and loosely coupled and ones with linear and complex interactions. The rationale here is to look for failure dependencies based on the quality or nature of interoperability in the early failure period.

7. Mediate Failure Period

The mediate failure period begins after the early failure period ends and extends until and if the relative obsolescence failure period begins. What types of interoperability failure mechanisms are expected to dominate in the mediate failure period?

The process depicted in figure 6 is used to understand the failure mechanisms that are likely to dominate in the mediate failure period. In this period, the two systems have a history of interoperating and the majority of the intended functionality of the systems have been exercised and made to work. Here two types of circumstances are postulated to lead to interoperability failures; those arising from rare functional threads that trigger latent defects and those arising from new modes of operation and procedures that lead to unintended functionality that is not provided for in the system design implementation.

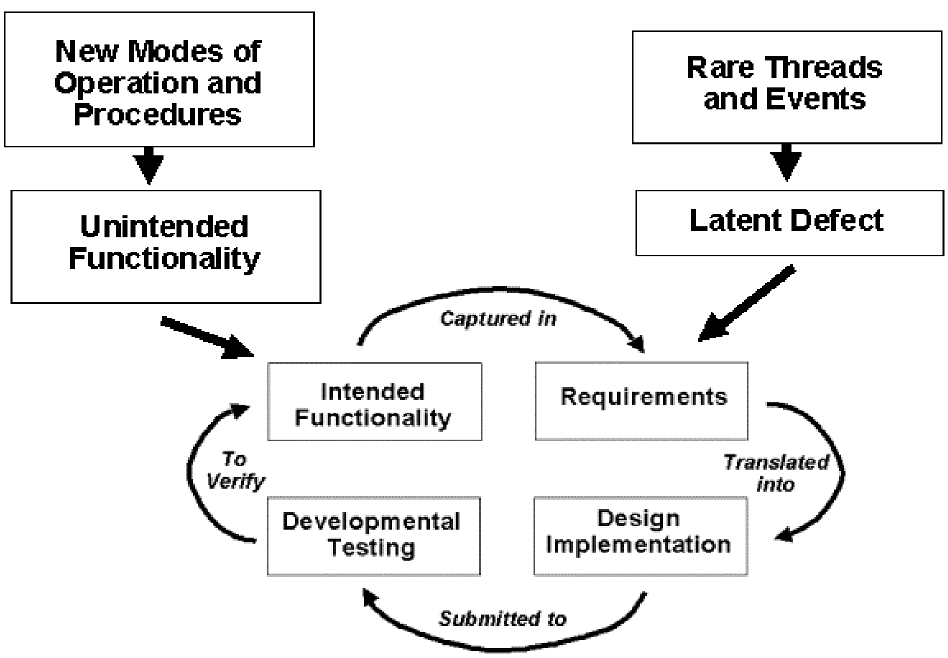

Figure 6. Process diagram used to discuss causal relationships for the mediate failure period failure mechanisms.

Root causes for defects associated with rare functional threads and events are the same as those identified under the development process described in the early failure period.

Root causes for defects associated with new modes of operation and procedures are similar to those arising in the requirements phase of the development process. The difference here is that this unintended functionality would not normally be captured in the requirements.

Based on the preceding discussion of the causal relationships postulated to be behind failure mechanisms in the mediate failure period the following hypothesis is generated:

HYPOTHESIS: Interoperability failure mechanisms expected to cause most of the failures in the mediate failure period stem from 1) rarely exercised functional threads and events and 2) new operational modes and procedures.

The following system selection criteria and rationale are offered to guide the selection of 15 C4ISR systems for initial study to look for evidence to refute or lend credence to the hypothesis and the mediate failure period for a system interoperability life distribution model. The systems of interest here should have been used in warfighting experimentation, forward looking exercises, new operational contexts, or have experienced an interoperability failures not attributable to the early or relative obsolescence failure periods.

1. The system should have been interoperating for at least 18 to 24 months before experiment, exercise, or interoperability failure occurs. The rationale here includes getting beyond the early failure period.
2. The systems should include ones that are tightly and loosely coupled and ones with linear and complex interactions. The rationale here is to look for failure dependencies based on the quality or nature of interoperability in the mediate failure period.

8. Relative Obsolescence Failure Period

The relative obsolescence failure period occurs if and when the number and scale of software and hardware upgrades in one system begin to outpace those of another system. What types of interoperability failure mechanisms might one expect to see dominating in the relative obsolescence failure period?

The process depicted in figure 7 used to understand the failure mechanisms that are likely to dominate in the relative obsolescence failure period. They are the same process-related mechanisms that were discussed in the early failure period. The difference here is that these systems have a history of interoperation before the upgrade(s) and the interoperability failures will most likely be limited to those functional areas most affected by the upgrades. However, since complex systems are sometimes involved, unexpected problems could appear in other areas not directly involved with the upgrades. For this reason, regression testing techniques are often used to help check for defects that cause problems beyond the immediate modules being modified. [McConnell, 1998, pp. 215-219]

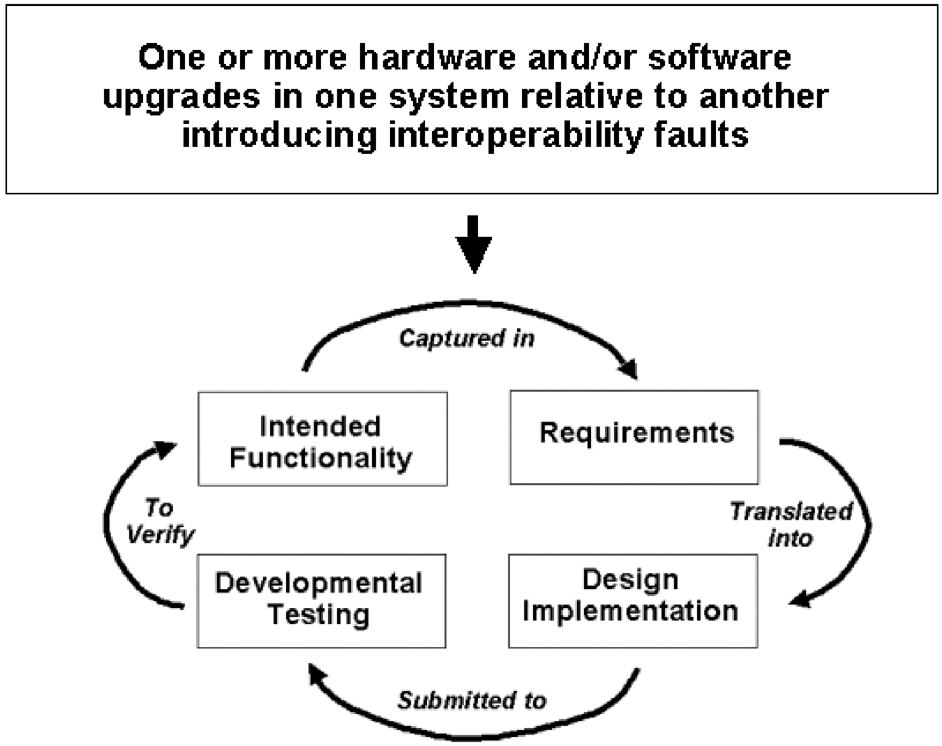

Figure 7. Process diagram used to discuss causal relationships for the relative obsolescence failure period.

Root causes for defects associated with upgrades are the same as those identified under the development process described in the early failure period.

Based on the preceding discussion of the causal relationships postulated to be behind failure mechanisms in the relative obsolescence failure period the following hypothesis is generated:

HYPOTHESIS: Interoperability failure mechanisms expected to cause most of the failures in the relative obsolescence failure period stem from 1) inadequate requirements, 2) design flaws, and 3) inadequate testing when one system is upgraded one or more times relative to the other.

The following system selection criteria and rationale are offered to guide the selection of 15 C4ISR systems for initial study to look for evidence to refute or lend credence to the hypothesis and the relative obsolescence failure period for a system interoperability life distribution model. The systems of interest here should be "legacy" systems not having been upgraded in several years.

1. The system should have been introduced more than 5 years ago and should not have received a major upgrade in the last 3 years. The rationale is to focus on older systems looking for instances where other interoperating systems have been upgraded.

2. The systems should include ones that are tightly and loosely coupled and ones with linear and complex interactions. The rationale here is to look for failure dependencies based on the quality or nature of interoperability in the relative obsolescence period.

9. Creating a Prediction Rule for Equipment Strings Based on the Theory

In this section, a brief sketch is provided of the general approach to be taken once some initial data has been collected and insights into the interoperability interaction and coupling between two systems over time has been gained.

The idea is to apply the "Science of Diagnostics" to extend the initial insights into the interoperability between two systems over time based on the data collected and analyzed for 45 systems. The goal is to develop the capability to predict an interoperability failure in a series of connected systems forming a equipment string. This will entail building Statistical Prediction Rules (SPR) to be used to make binary "yes" or "no" decisions about performing end-to-end interoperability testing on an equipment string. Achieving a statistically significant prediction rule may require collecting data on additional systems. [Swets et al., 2000]

The accuracy and utility of the diagnostic protocol based on the SPR will be characterized using Relative Operating Characteristic (ROC) analysis. ROC analysis provides a measure of diagnostic accuracy that is independent of fault event frequencies and decision criterion. The interested reader is referred to the paper by Swets, Dawes, and Monahan for a more complete discussion of these techniques. [Swets et al., 2000]

10. Next Steps.

The next steps for this research initiative include collecting the data required to refute or lend credence to the theory, refining the theory based on the collected data, determining the relationships between the causal factors and interoperability failures, building prediction rules based on the data, extending the data collection to a statistically significant number of cases, and building statistical prediction rules.

The primary data collection effort will focus on 45 systems with 15 systems targeted for each time period in the postulated life distribution model. Initially, one to three systems will be investigated to discover the interview and data collection processes that are the most effective in uncovering the interoperability history of a system and addressing the experimental objectives. Then more investigators will be trained and begin collecting data on all 45 systems.

It is envisioned that data collection will follow two simultaneous paths. The first path consists of searches of known reliability, trouble report, and issues databases for relevant information on the system under investigation. The second path consists of structured interviews with the system program managers, in-service engineering agents, installers, and operators to garner anecdotal evidence, stories, and leads to other sources of relevant knowledge.

11. Summary

A theory of interoperability failures has been developed and presented in this paper. It considers the interaction of two systems over time to postulate a life distribution model with three distinct time periods: early, mediate, and relative obsolescence. A causal analysis that focuses on intended functionality, requirements, design implementation, and developmental testing was used to explain the existence of these three time periods. Interoperability and complexity were discussed in terms of system interaction and coupling. Criteria were provided for selecting systems to study in hopes of refuting or lending credence to the theory. An approach for extending the theory to create statistical prediction rules for equipment strings was also discussed.

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8TH INTERNATIONAL COMMAND AND CONTROL RESEARCH AND TECHNOLOGY SYMPOSIUM
"INFORMATION AGE TRANSFORMATION"
JUNE 17-19, 2003
NATIONAL DEFENSE UNIVERSITY
WASHINGTON, DC

A Theory of Interoperability Failures

Track 1: Coalition Interoperability
1330-1400, Wednesday, June 18, 2003
Presented by Michael S. McBeth

Table of Contents

Outline

Backups

Introduction

- Achieving interoperability among C4ISR systems remains a challenge for the U.S. Department of Defense
- Progress has been made in recent years through the use of:
  - directives and guidance
  - increased awareness
  - emphasis on capability vice platforms
  - integrated architectures
  - mission capability packages
- However ...

Introduction

One element missing from this mix is a coherent, verifiable theory of interoperability failures that captures the causes of interoperability faults in a form that practitioners can use to avoid problems in their own work

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Introduction

- Purpose: Develop a theory of interoperability failures that can be confirmed through objective evidence
- Goal: To be able to efficiently collect the data required to create and validate prediction rules that can be used to make diagnostic decisions about conducting end-to-end interoperability testing of C4ISR equipment strings

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Earlier Related Work

- "*Interoperability: A New Paradigm*" 1999 paper by Paul Sutton where an analogy is drawn between interoperability and electronic equipment reliability
- Two papers presented in at last year's ICCRTS & CCRTS by John Hamilton, Pam Sanders, CAPT John Melear, and George Endicott where interoperability is dealt with using an engineering life cycle model

See [Sutton, 1999] [Hamilton et al., 2002a] [Hamilton et al., 2002b]

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U.S. DoD Definition

"(1) The ability of the systems, units, or forces to provide services to and accept services from other systems, units, or forces, and to use the services so exchanged to enable them to operate effectively together, and (2) the condition achieved among communications-electronics systems or items of communications-electronics equipment when information or services can be exchanged directly and satisfactorily between them or their users. The degree of interoperability should be defined when referring to specific cases."

Source [CJCS, 2000]

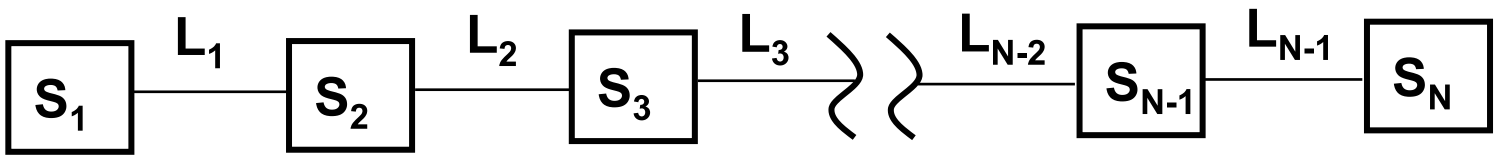
Sutton's Definitions

End-to-end interoperability ***– "The probability of successful interoperation of all subscribers in a network under specified conditions for a given mission time."***

Interoperability failure ***– "The inability of the network to meet specified interoperability levels, conditions, and requirements, such as minimum acceptable data transfer rate, quality of service, and maximum allowable latency."***

Source [Sutton, 1999]

Background Definitions



***<u>Equipment string</u>* – a serial sequence of N systems connected by N-1 links that provides a communications path between users to exchange information**

***<u>Functional thread</u>* – a construct consisting of the equipment string input, equipment string output, a description of the transformations to be performed and the conditions under which this should occur.* See [INCOSE, 2000]**

Definitions for this Paper

Interoperability ***– "The ability of two or more systems to exchange information and to mutually use the information that has been exchanged."*** **[IEEE, 1988]**

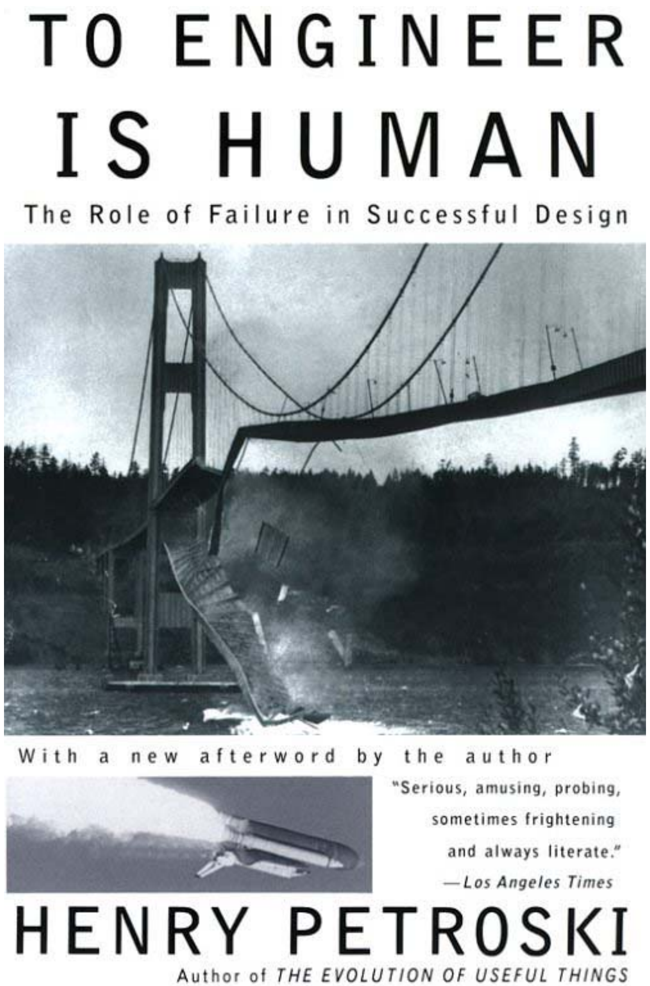
Interoperability fault ***– A defect or condition related to system interaction that causes a reproducible malfunction in the ability of two or more systems to exchange information and use the information once exchanged. Note: a malfunction is considered reproducible if it occurs consistently under the same circumstances.*** **[Adapted from FS-1037C, 1996]**

Definitions for this Paper

***Interoperability failure* – "The inability, due to an interoperability fault, of two or more systems to exchange information and to mutually use the information once exchanged."**

Why do we need a theory of interoperability failures?

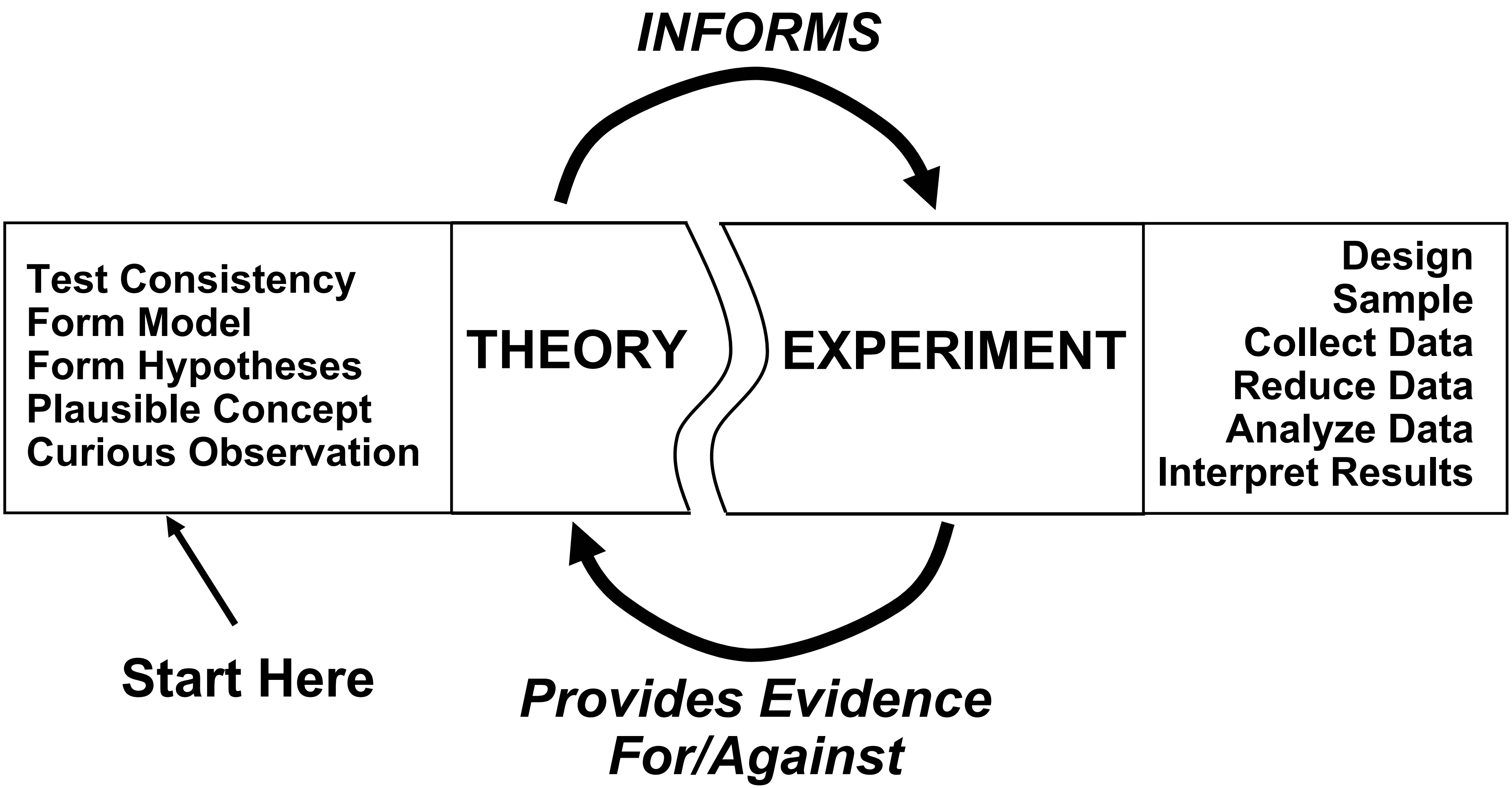
The Role of Failure in Design



True advances in engineering design often depend on gaining a deeper understanding of how things fail. Think of 19th century steel railroad bridges and the de Havilland Comet aircraft.

Why should we think that designing system of systems that resist interoperability failures would be any different?

Reinforcing Relationship Between Theory and Experiment



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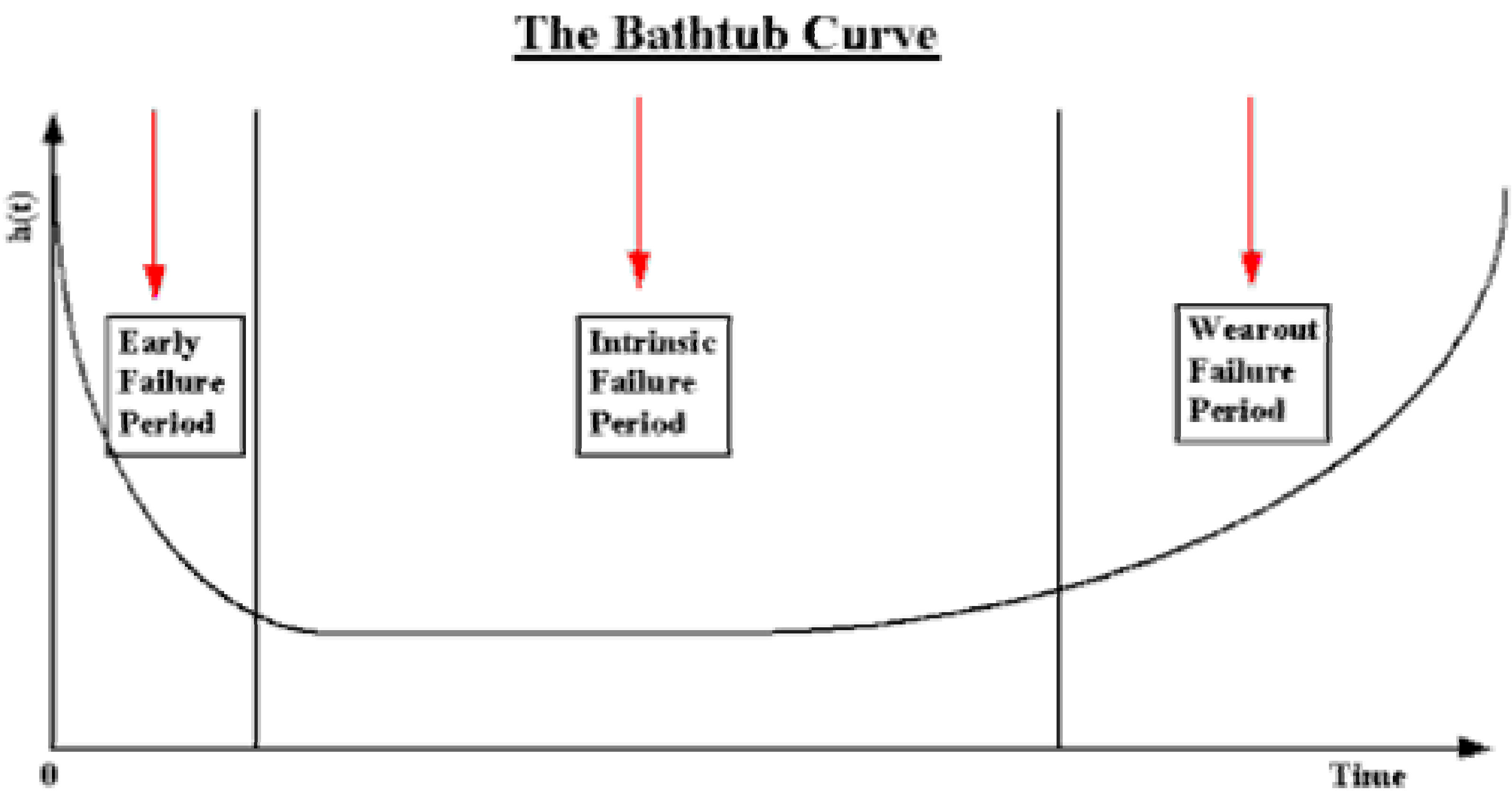
Sutton's Analogy

- Interoperability: A New Paradigm
- Draws on the analogy of electronic equipment reliability to postulate a theory of interoperability failures
- Assumes random interoperability failures and a constant interoperation failure rate
- Leads to a large list of potential contributing factors to be studied

On the right track ... But, Challenge the Assumptions!

See [Sutton, 1999]

Reviewing the Bathtub Curve



Source [NIST, 2003]

Extending Sutton's Analogy

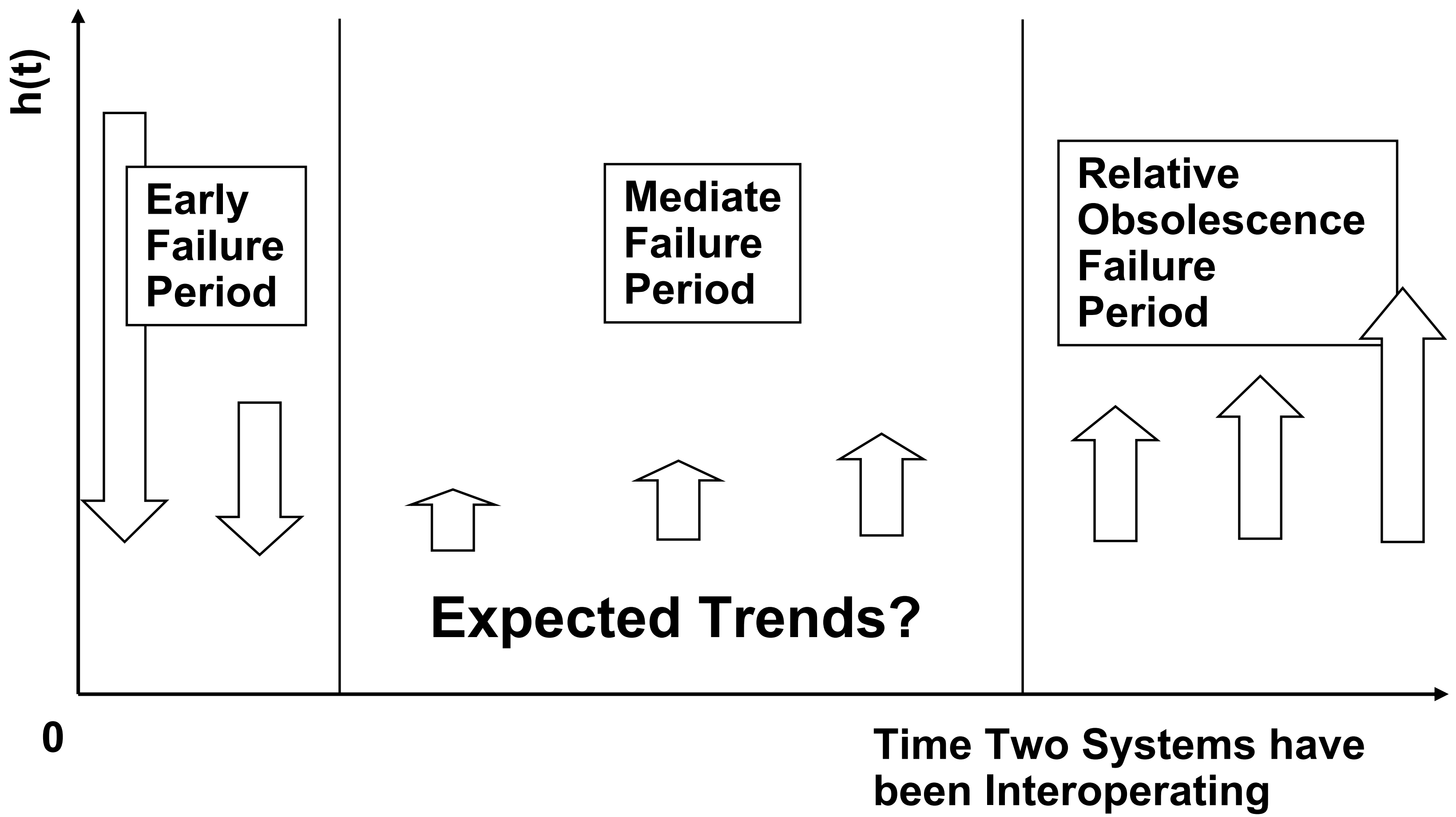
- **Consider interoperability interaction between two systems over time**
- **Assume resulting model can be applied to equipment strings by pair-wise extension**
- **Power of analogy is that "*different failure mechanisms may tend to dominate at different times*"**
- **Time in this analogy is the time that two systems have been interoperating**

See [Sutton, 1999]

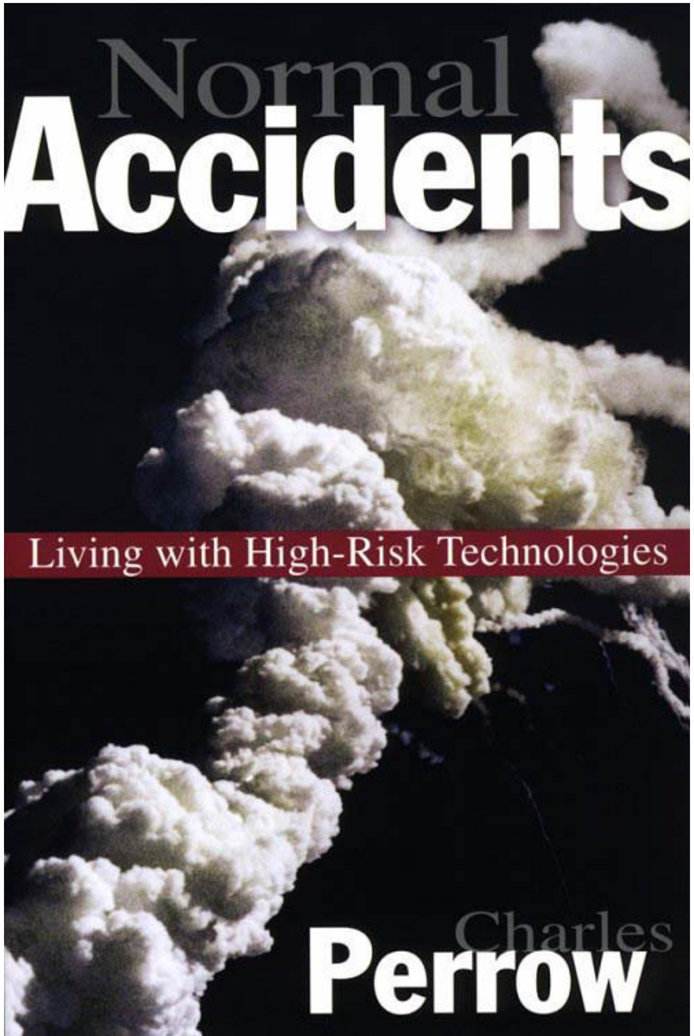
Three Postulated Time Periods

- **Early — relatively high failure rate; the two systems have little or no experience interoperating with each other.**
- **Mediate — relatively low failure rate; the two systems have some experience and a history of interoperating with each other.**
- **Relative obsolescence — relative failure rate that increases over time; occurs when one system's hardware or software is upgraded faster than the other system.**

Three Postulated Time Periods



Interoperability and Complexity



Critical System Properties: Survey and Taxonomy[1]

Original version published in *Reliability Engineering and System Safety*, Vol. 43, No. 2, pp. 189–219, 1994

John Rushby
Computer Science Laboratory
SRI International
Menlo Park CA 94025 USA

Technical Report CSL-93-01, May 1993
Revised February 1994

More to the picture than a life distribution model based on the time two systems have been interoperating — character of system-to-system interaction also need to be considered…

See [Perrow, 1984] **See [Rushby, 1994]**

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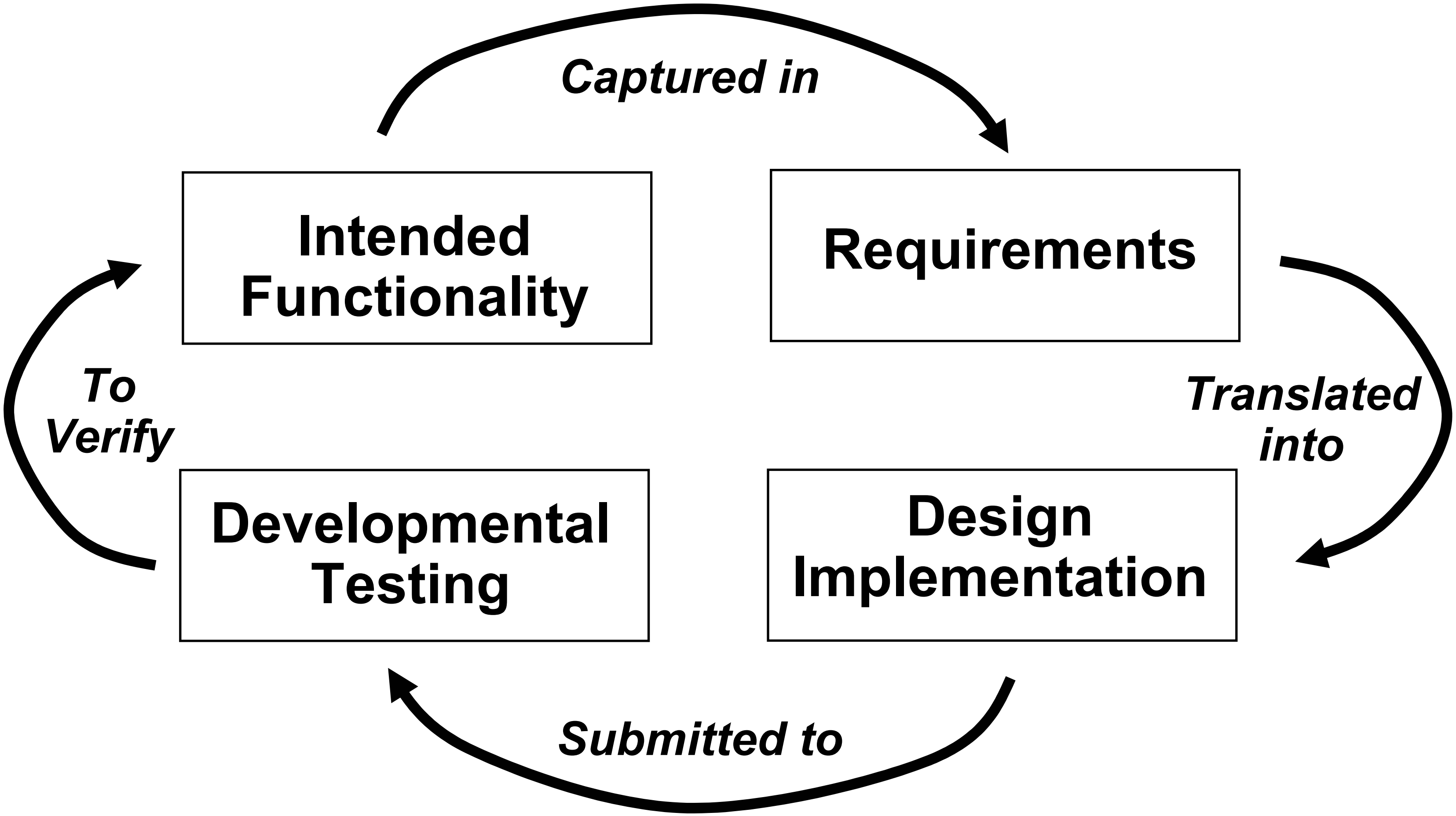
System Interaction & Coupling

***<u>Interaction</u>* – "Ranges from "linear" to "complex," refers to the extent to which the behavior of one component in a system can affect the behavior of other components."**

***<u>Coupling</u>* – "can range from "loose" to "tight," refers to the extent to which there is metaphorical "slack" or "flexibility" in the system. Loosely coupled systems are usually less time constrained than tightly coupled one, can tolerate things being done in different sequences than those expected, and may be adaptable to different assumptions than those originally considered."**

Source [Rushby, 1994, Chapter 4, p. 42]

Early Failure Period



Both systems go through this process … faults can be introduced in first three blocks and not detected in the last

Early Failure Period

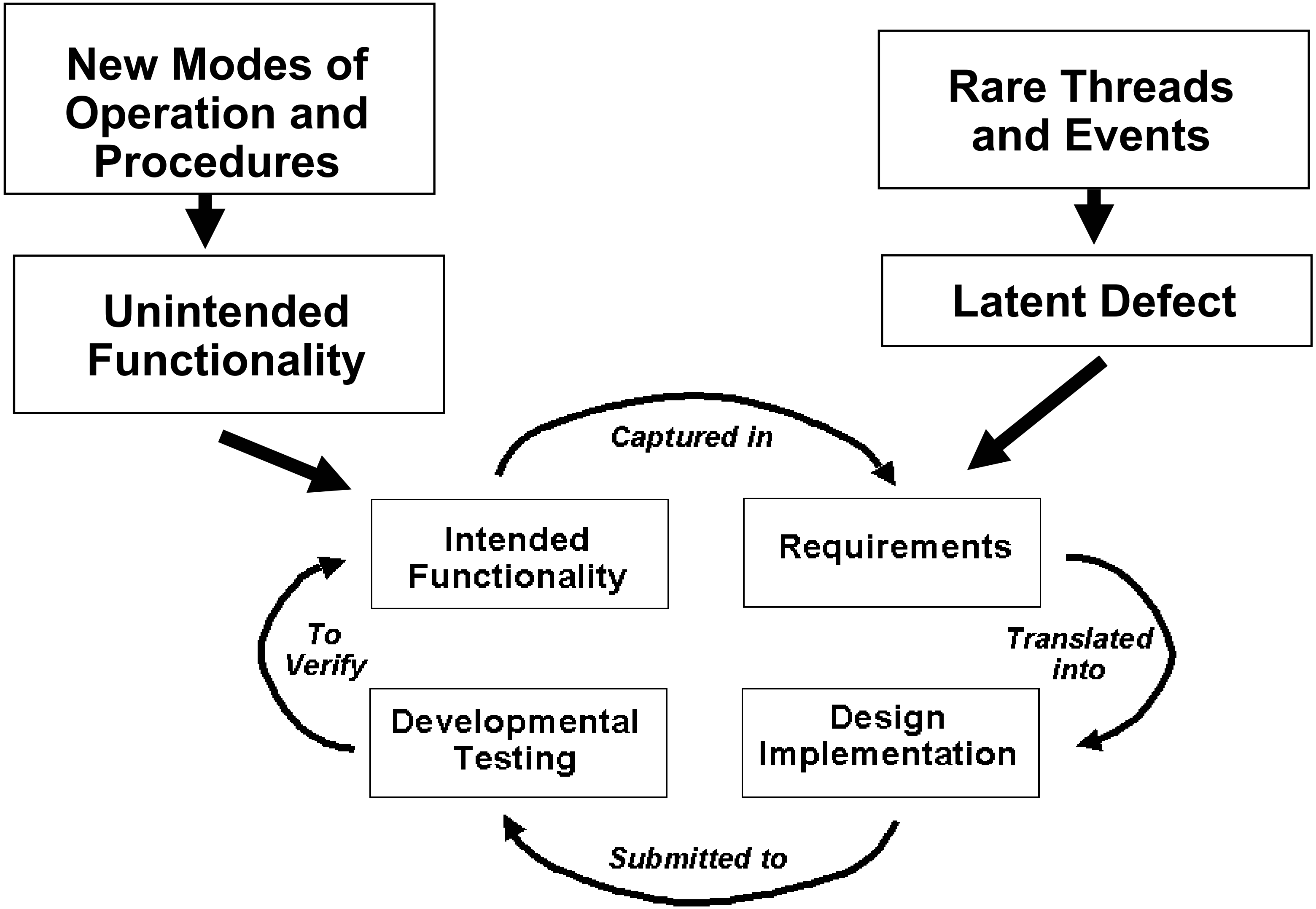
Expected causes:

- Missing or inadequate requirements
- Design flaws
- Inadequate testing

System selction criteria:

- System introduced in last 5 years
- First use or major upgrade
- Mix of 1) tightly and loosely coupled and 2) linear and complex interactions

Mediate Failure Period



Mediate Failure Period

Expected causes:

- **New modes of operation and procedures leading to unintended functionality**
- **Rare threads or events that trigger latent defects**

System selction criteria:

- **Systems interoperating for at least 18 to 24 months before experiment, exercise, or failure occurance.**
- **Mix of 1) tightly and loosely coupled and 2) linear and complex interactions**

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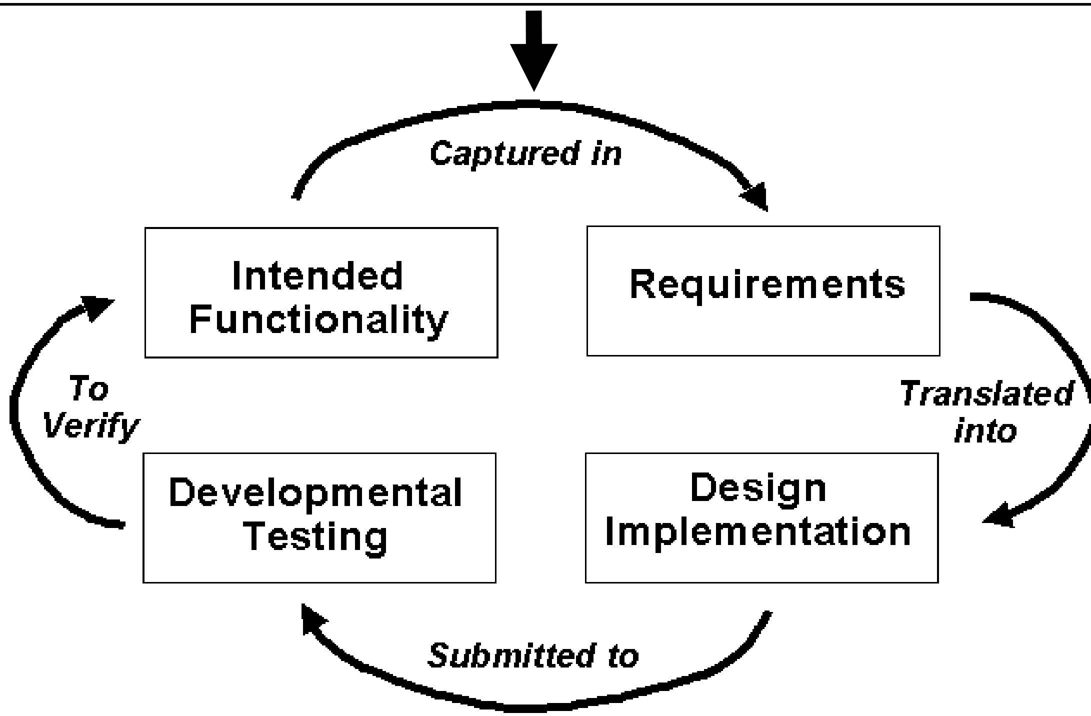
Relative Obsolescence Failure Period

One or more hardware and/or software upgrades in one system relative to another introducing interoperability faults



Relative Obsolescence Failure Period

Expected causes:

- Missing or inadequate requirements
- Design flaws
- Inadequate testing

System selction criteria:

- System introduced more than 5 years ago
- No major upgrades in last 3 years
- Mix of 1) tightly and loosely coupled and 2) linear and complex interactions

Creating a Prediction Rule Based on the Theory

- First, build a Statistical Prediction Rule (SPR) to make binary “yes” or “no” decisions about a paricular system-to-system pair will have an interoperability failure
- Then, extend the resulting model to equipment strings using pair-wise analysis

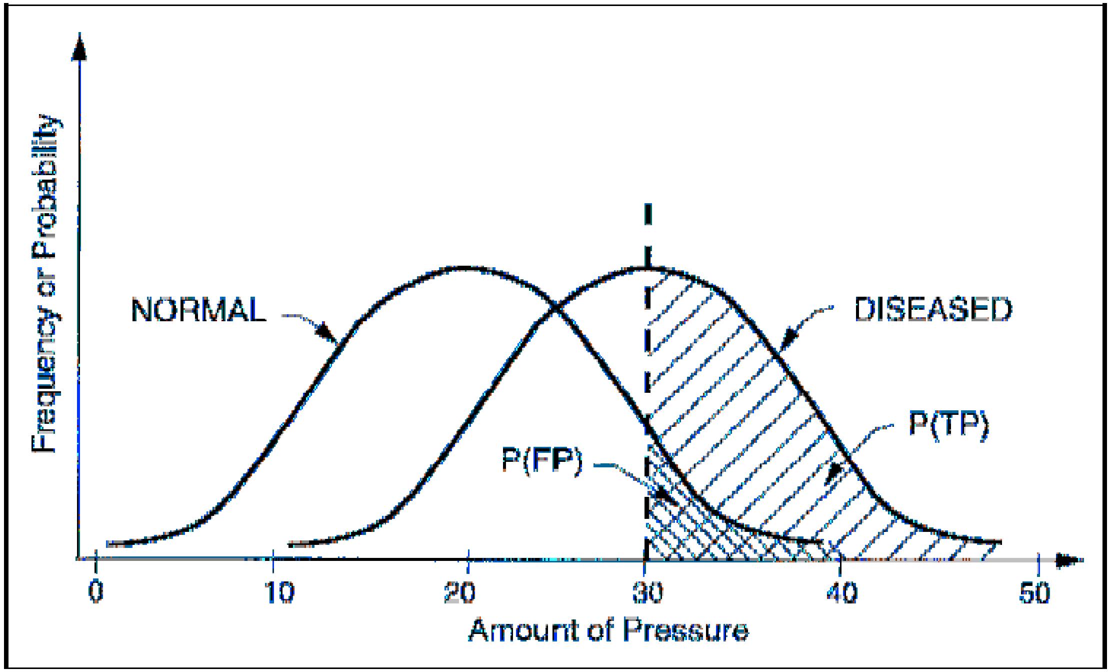
Statistical Prediction Rules

- Statistical analysis is used to quantify the power of candidate predictive variables to discriminate between positive and negative instances of the diagnostic alternatives under study
- Variables may be added to a SPR and assigned their respective weights in a stepwise fashion
- An SPR can be constructed using both <u>objective</u> and <u>subjective</u> factors
- An SPR ends up being a set of <u>variables</u> and <u>weights</u>

From [Swets et al., 2000]

Statistical Prediction Rules

Consider this example to understand how Statistical Prediction Rules work. Shown here are probability distributions of eye pressures for both healthy people and those with glaucoma. Establishing a decision threshold of 30 for diagnosing patients with glaucoma results in an accurate diagnosis of about 50% of the diseased population, P(True Positive), while about 10% of the healthy population will be mis-diagnosed with the disease P(False Positive) or false alarms.

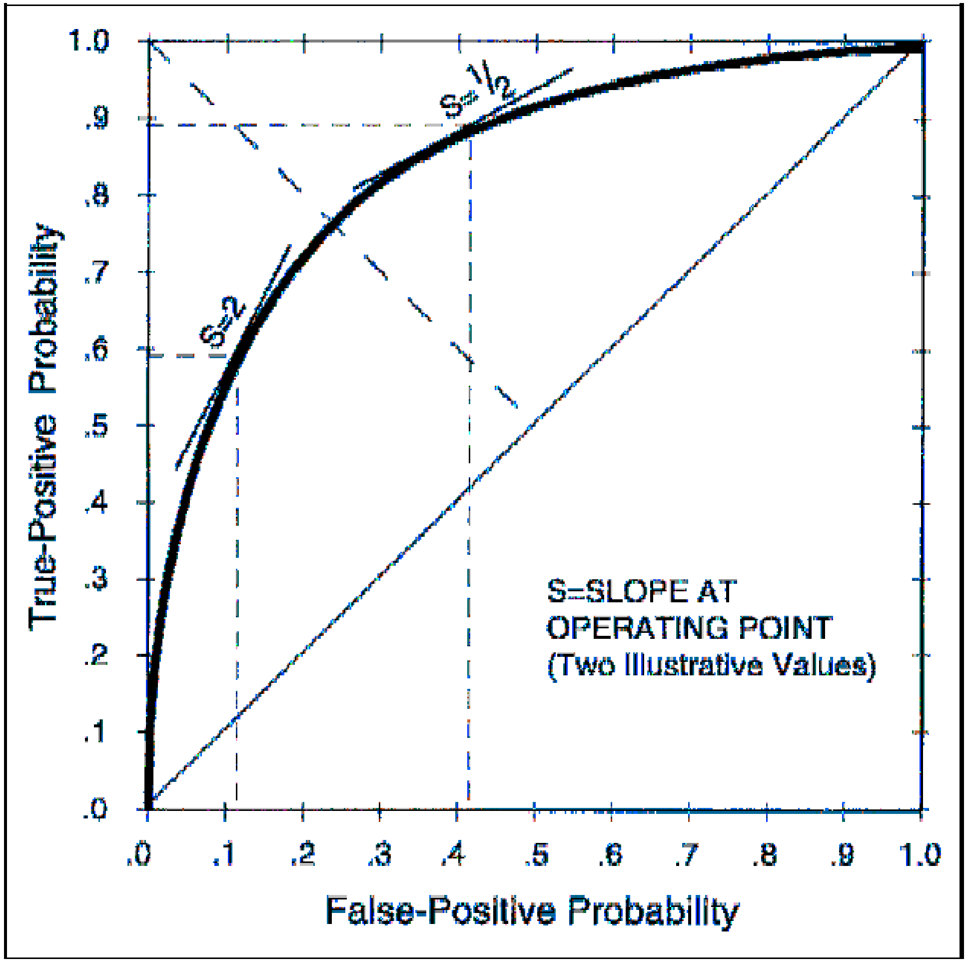


From [Swets et al., 2000]

Receiver Operating Characteristic

A Receiver Operating Characteristic (ROC) curve is created by plotting the areas under the distributions for each possible threshold value. For example, a threshold of 30 corresponds to the point where P(FP) x-axis = 0.1 and P(TP) y-axis = 0.5. This represents an approx threshold of S = 2. The diagonal line represents "chance" accuracy of 50/50 ratio True Positive to False Positive.

From [Swets et al., 2000]



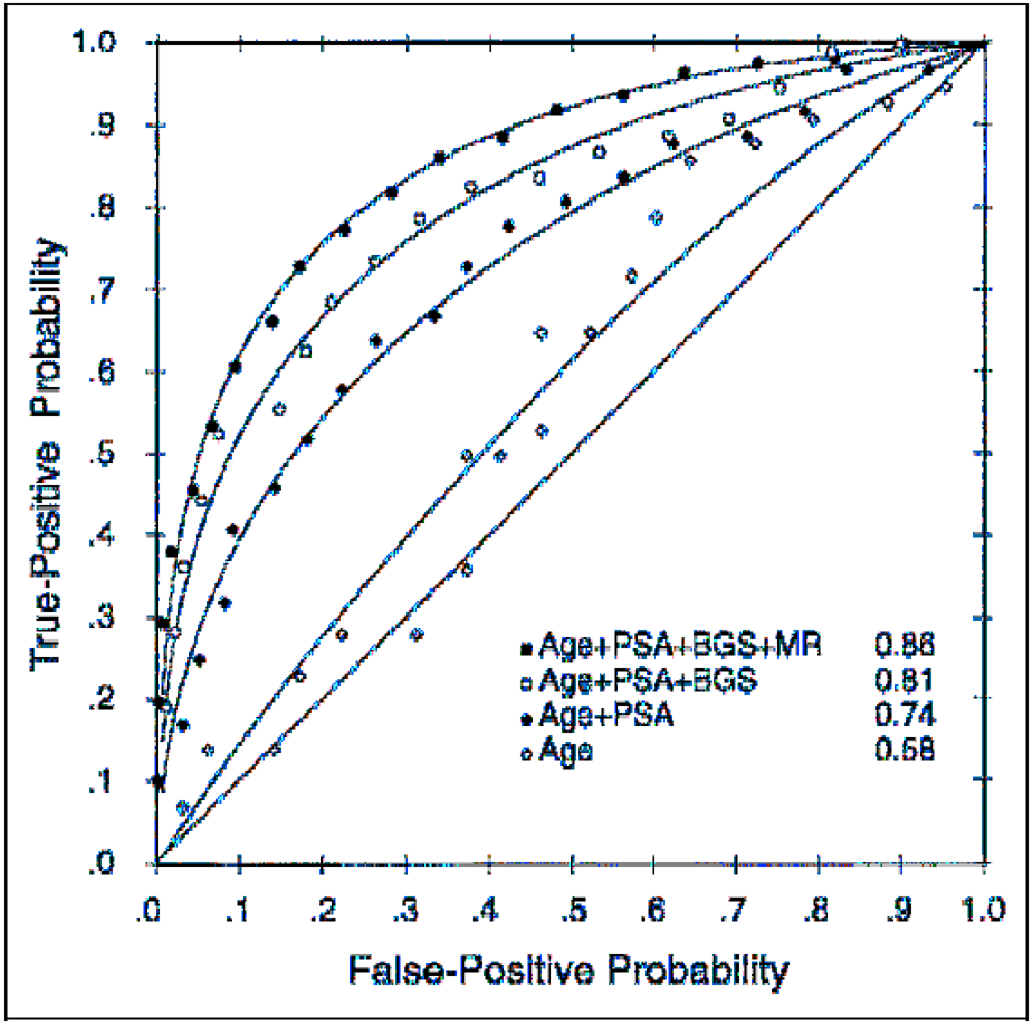
Where are these techniques being used?

- **Numerous fields including medical diagnostics, predicting violence among criminals, weather forecasting, law school admissions, aircraft cockpit warnings, qualility of sound in opera houses, and predicting wine vintage quality.**
- **The following example is taken from the field of medical diagnosis where several different pieces of information are combined to judge whether prostrate cancer has spread in a patient...**

From [Swets et al., 2000]

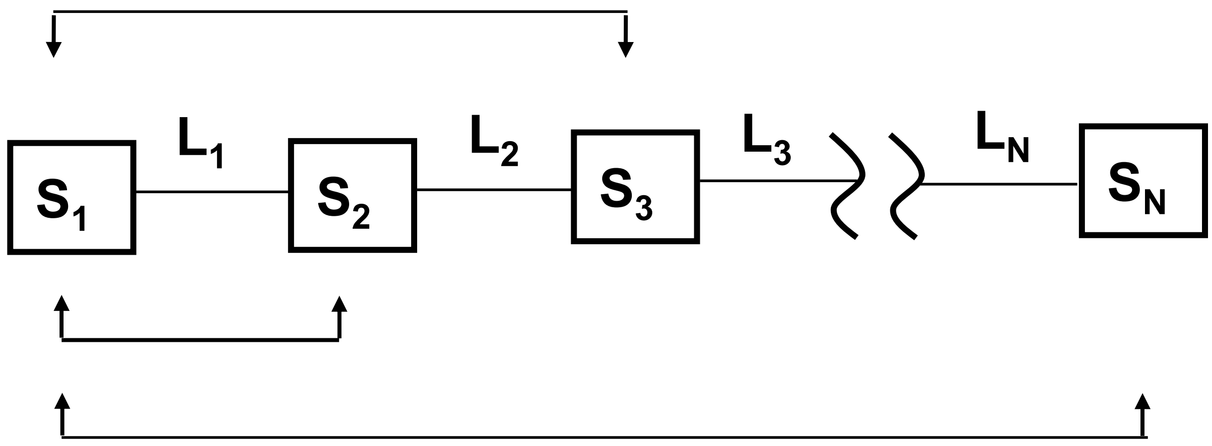
SPR for Prostrate Cancer

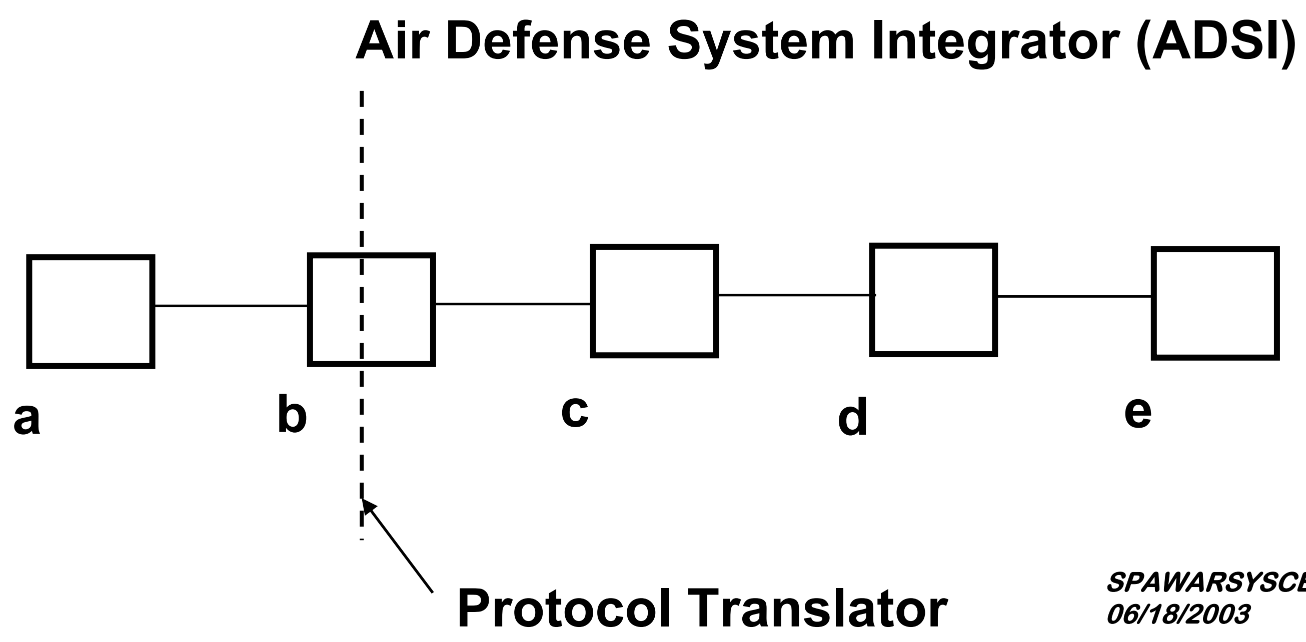
Empirical Receiver Operating Characteristic (ROC) curves for determining the extent of prostrate cancer, based on SPRs (Statistical Prediction Rules), using one, two, three, or four predictor variables. The closer to the upper left, the higher the SPR's accuracy.



From [Swets et al., 2000]

Issues with Pair-wise Extension





Next Steps

- Refine initial system selection criteria
- Collect and analyze data on initial systems to be studied
- Investigate establishing a center for studying interoperability failures at U.S. JFCOM, J8, Joint Interoperability and Integration (JI&I)
- Leverage NIST efforts and tools. (Error, Fault and Failure data collection and analysis tool)
- Foster a continuing dialog through this forum and others

Summary

- A theory of interoperability failures has been developed
- It considers the interaction of two systems over time
- Postulates three distinct time periods:
  - Early
  - Mediate
  - Relative obsolescence
- Need to study some representative systems to refute or lend credence to the theory

Questions?

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Backups

Sutton's Problems with LISI

1. Does not address specific electrical interfaces
2. Does not address objects and object model compatibility
3. Assigns nominal values based on documentation, not objective system performance
4. Does not take into account that some systems may not need higher levels of interoperability to be considered successful
5. Does not explain how interoperability can be controlled, changed, or improved

Source [Sutton, 1999]

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